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RADIALLY CONVERGENT PROTON BEAMS FROM A CYLINDRICAL DOUBLE DIOD--ETC(U)
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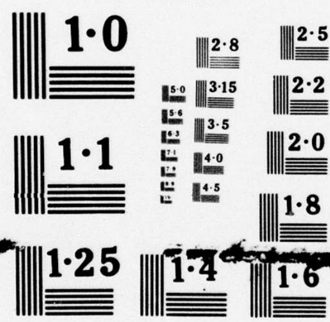

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Radially Convergent Proton Beams from a Cylindrical Double Diode.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A cylindrical double diode is used to produce a radially convergent proton beam. This device exhibits both pinching and, to a lesser degree, reflexing of the electrons. The proton current density incident on the inner cathode is larger than the ion current density anticipated for bipolar space charge flow. The current density of ions extracted through the cathode has been intensified by at least a factor of 7 as a result of geometric focusing.

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CONTENTS

RADIALLY CONVERGENT PROTON BEAMS FROM A CYLINDRICAL DOUBLE DIODE

I. Introduction

Pulsed proton beams with current density in excess of 1 kA/cm^2 and with energy $\simeq$ 1MeV have recently been generated with various devices.[1-3] The potential applications of these beams include formation of ion rings,[4-6] excitation of gas lasers,[7,8] hybrid systems[9] and inertial confinement.[10,11] However, the last application requires a proton current density considerably higher than those presently available. Geometric focusing is a convenient way to increase the current density of the ion beams. Promising results have already been obtained with geometric focusing using proton beams generated by pinched electron diodes[12] and magnetically insulated diodes.[13]

In this report we describe a new device, the cylindrical double diode, which also produces radially converging ion beams. However, unlike the magnetically insulated diode, the new device has the potential to produce ion beams having current densities considerably higher than that predicted from $J_{io} = \left[m_e/M_i\right]^{1/2} J_e$, where m_e/M_i is the electron-ion mass ratio and J_e is the electron current density. The present results show that the proton current density at the anode is approximately a factor of 2.7 greater than J_{io}. The new device belongs to the category of reflexing electron systems.[1,2,15,16] It is conceivable that by suitable modifications, the device could generate ion current densities at the

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anode that exceed J_{io} by two orders of magnitude as is the case with other electron reflecting systems.[1,2]

II. Discussion

A cylindrical double diode consists of two grounded concentric cathodes and an anode which is at positive potential (Fig. 1). The anode is a thin plastic film supported by axial metal wires. Electrons are emitted from both cathodes and accelerate toward and pass through the anode film. Plasma is formed on the anode plastic and ions accelerate toward both cathodes. Because the inner cathode is highly transparent to the ions, the ions ballistically flow radially inward inside the inner cathode.

In passing through the anode, elastic scattering and inelastic losses reduce the radial velocity of the electrons. Moreover, the electron trajectories are curved because of the azimuthal self-magnetic field B_θ produced by currents flowing in the anode and inner cathode (Fig. 2) and because of the axial component of the electric field due to space charge and fringing of the applied field. The scattering and losses at the anode, and the bending of the orbits by B_θ and E_z limit the number of anode crossings made by an electron.

The ratio of ion current to electron current in a given gap is expected to be proportional to the ratio of the typical residence time in the gap of an electron to that of an ion.[17] The number of reflexing electron anode transits and the amount of trajectory curvature influence the typical electron residence time.

To gain some insight on the effect of B_θ on the orbits, the relativistic equations of motion have been integrated neglecting the space

charge field and the axial component of the applied field. Results are shown in Fig. 3.

These orbits were calculated by a non-self-consistent numerical integration of the relativistic equations of motion having assumed the radial and axial functional dependence of B_θ and E_r (= radial electric field). Because the branching of the anode current into the two gaps depends on the ion currents and the actual electron distributions which are not known, the ratio of the current in the inner cathode to the anode current was approximated as that resulting in two independent cylindrical diodes without ion current according to the results of Langmuir and Blodgett.[18] Therefore, the trajectories of Fig. 3 are approximate even when E_z is small.

For a single gap diode of infinite axial length, the effect of trajectory curvature resulting from B_θ on the ion current density J_i has been calculated by Bergeron.[19] When $I/I_{crit} \sim \frac{1}{2}$, where[20] $I_{crit} \simeq 8500\ (\gamma^2-1)^{\frac{1}{2}}/\ln(r_c/r_a)$, and $(r_a-r_c)/r_c \leq 1$, then J_i/J_e is approximately 2 to 3 times $\sqrt{m_e/M_i}$, where J_i and J_e are the ion and electron current densities and where the applied potential is approximately 0.5 MV. However, for a double diode the electrons emitted from the outer cathode contribute to the electron density near the anode in the inner gap. If the current in the inner gap is almost equal to the critical current, then the electrons emitted from the inner cathode will not contribute to the electron density in the outer gap in the vicinity of the anode plastic.

The trajectories shown in Fig. 3 also reveal that the electrons congregate near the anode support wires at axial positions a few

centimeters on both sides of the anode plastic. In practice, this electron pinching can propagate along the wire. Ions from plasma produced on the surface of the rod will also be accelerated thereby contributing to both the inward and outward current.

III. Experiment

The cylindrical double diode studied experimentally is shown in Fig. 1. A 325 kV, 60 ns maximum duration positive pulse from the NRL Seven Ohm Line Generator is applied to the anode. The anode is a strip of 12.5 μm thick polyethylene film typically 0.5 to 1.0 cm wide mounted on 8 parallel brass rods 1.5 mm in diameter equally placed about a 5.1 cm diameter circle. The carbon outer cathode with 7.0 cm ID and 7 mm axial length is concentric with the 2.0 cm diameter copper screen inner cathode.

The number of protons per pulse which pass through the 65% transmission screen of the inner cathode is determined by a nuclear activation technique.[21] The protons strike cylindrical targets of boron nitride which are mounted on a grounded wire located along the axis of the device. By coincidence counting the annihilation radiation due to positrons produced by the $^{14}N(p,\gamma)^{15}O(\beta^+)^{15}N$ nuclear reaction, the number of protons per pulse with energies above the 277 keV resonance of the reaction can be calculated from the known thick target yield. A correction is not made for the loss of ^{15}O nuclei prior to the coincidence counting (blow off). This loss may occur because of target ablation and surface heating by the beam. Previous investigations have shown that only three-quarters of the radioactive ^{13}N nuclei produced by a proton beam with a current density of 40 A/cm^2 are

present in BN target samples during the coincidence counting.[22] Because the correction factor has a quantitatively unknown dependence on current density, the results reported here are conservative lower bound estimates. The correction is apparently larger for high current densities.

For a peak anode current of approximately 15 kA, damage on the anode plastic and brass support rods indicates a 3 mm deflection of the electrons emitted from the edge of the cathode closest to the generator. It is found that the impedance depends on the width and the axial position of the anode plastic. Greater surface area anode films result in lower impedances. The maximum number of protons per pulse is obtained with a 7 mm wide anode plastic strip positioned so that its edge closest to the generator is also 3 mm from the cathode edge which is closest to the generator. This is consistent with the electron trajectories of Fig. 3, but the agreement may be fortuitous, since E_z has been omitted in the calculation.

Evidence for the pinching shown in Fig. 3 is observed in the damage and erosion of the brass rod. This occurs at the tip and at an axial position approximately 1.5 cm from the edge of the outer cathode toward the generator. In addition, slight damage is observed elsewhere along the entire length (5 cm) of each of the brass rods. At the connections to the generator output, damage and erosion are also found. This suggests that the electron flow propagates along the wires.

The currents flowing in the anode and in the inner cathode shank were monitored with probes measuring azimuthal magnetic field. The probes were calibrated with a resistive shunt during a short circuit shot. For an applied voltage of 330 kV, $\gamma \sim 1.65$ and for the parameters

of the experimental device, the current in the inner gap $I_2 \approx 10.5$ kA and in the outer gap $I_1 \approx 4.5$ kA. The critical currents are $I_{crit} \approx 12.2$ kA in the inner gap and 31.3 kA in the outer gap. Therefore, in the inner gap $\frac{I_2}{I_{crit}} \sim 0.86$ consistent with large significant deflection of the electron orbits, and in the outer gap $I_{anode}/I_{crit} \sim 0.48$ consistent with moderate deflection. Although the current density cannot be inferred precisely because the cathode area emitting electrons is not well known, the total current densities at the cathode are estimated to be $\leqslant 1.3$ kA/cm^2 in the inner and 0.29 kA/cm^2 in the outer gap. These values are about 1.3 times the current densities anticipated for separate electron only cylindrical diodes. Using a scintillator-photodiode detector, the ion pulse is found to be approximately trapezoidal. For the inner gap peak ion currents of 492-A (average current 328-A for 30 ns) are inferred from the 4×10^{13} protons per pulse that pass through the 65% transmission inner cathode. This peak current is about twice $[m_e/M_i]^{\frac{1}{2}}$ times the electron current in the inner gap. From the axial length of the activation target, a maximum estimate of the relevant cathode surface area of 8 cm^2 is obtained. Therefore, the corresponding ion current density incident on the inner cathode is greater than 61.5-A/cm^2 peak (41-A/cm^2 average).

The ballistic flow of the ions inside the cathode was studied by measuring the activation induced by the proton flux onto BN activation targets of various diameters. Fig. 4 shows the time average current density for targets of 0.64 cm, 0.16 cm, and 0.08 cm radius. Each data point is the average of 3 or more shots. Because the axial

length (2 cm) of the targets was greater than the axial extent of the majority of the ion flow, the values of current density shown in Fig. 4 are conservative lower bounds.

The ion flow extracted through the cathode is observed to be intensified by a factor greater than 7. The discrepancy with a functional behavior inversely proportional to radius may be because of difficulty in coaxial alignment or because of greater blow off with slender targets which have high current density. However, 0.7 of the flux at 0.64 cm radius reaches the target at 0.08 cm radius. Correspondingly, the upper limit on the angular error of focus in the transverse direction is 4°.

Experiments at higher applied potential (410 kV) have resulted in time-average current densities of 45-A/cm^2 through the cathode and 70-A/cm^2 at a radius of 0.64 cm. In this case activation targets could not be used reliably at smaller radii because of target damage and associated blow off.

IV. Summary

Radially convergent proton fluxes have been produced in a cylindrical double diode. Geometric focusing has been observed with an intensification of ion current density by a factor of at least 7. Ion fluxes equivalent to hundreds of amperes per square centimeter may be obtainable from this device in its present form. However, the possibility exists that by suitable modification, the oscillating electrons will reflex several times through the anode resulting in high ion current density. This device could provide a compact, practical high ion current density source.

V. Acknowledgments

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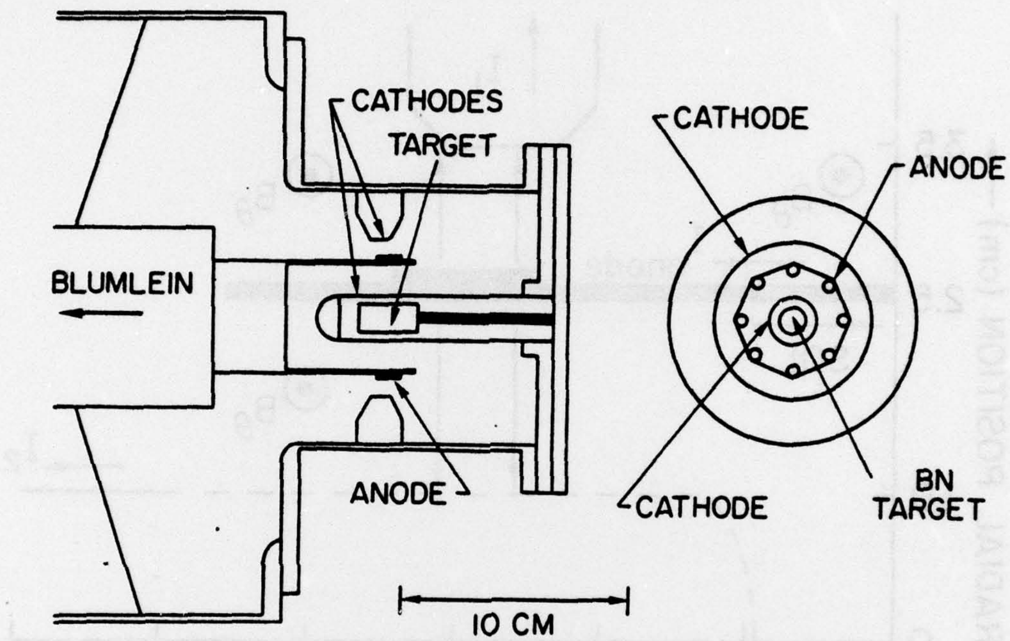

Fig. 1 — Schematic of the experiment

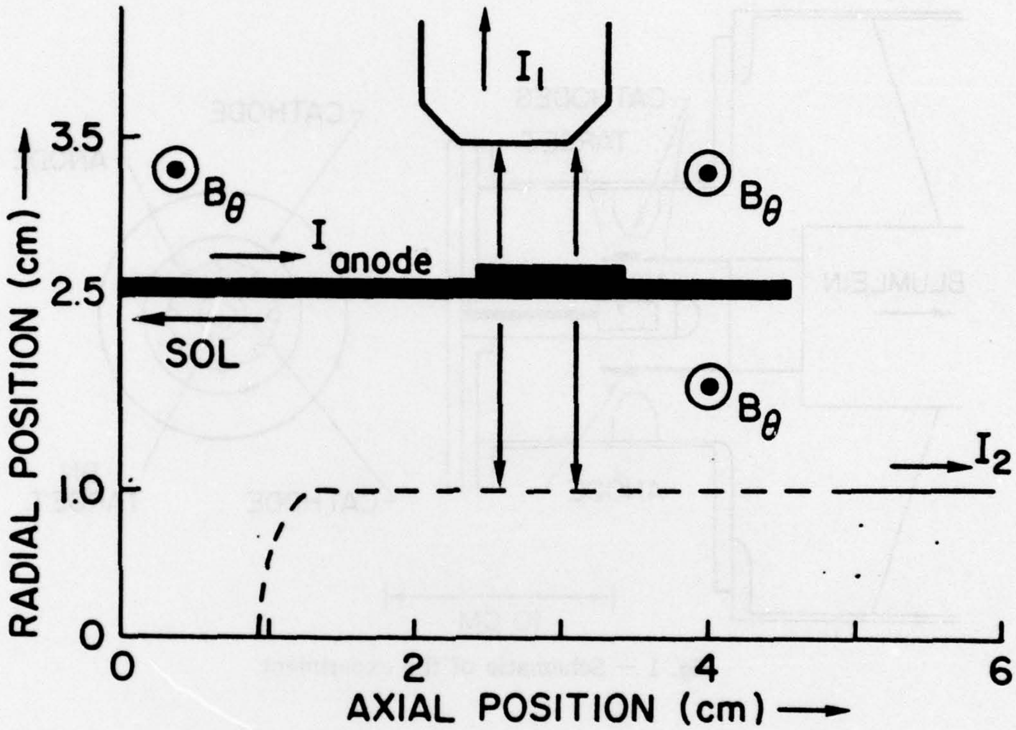

Fig. 2 — Current paths in the cylindrical double diode

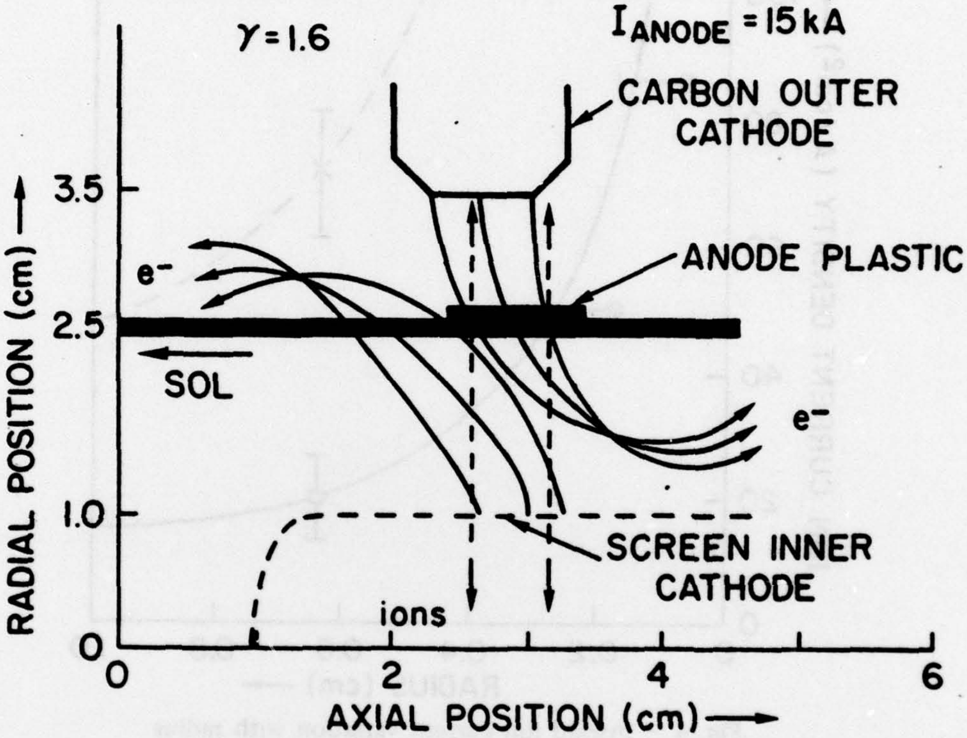

Fig. 3 — Typical particle trajectories

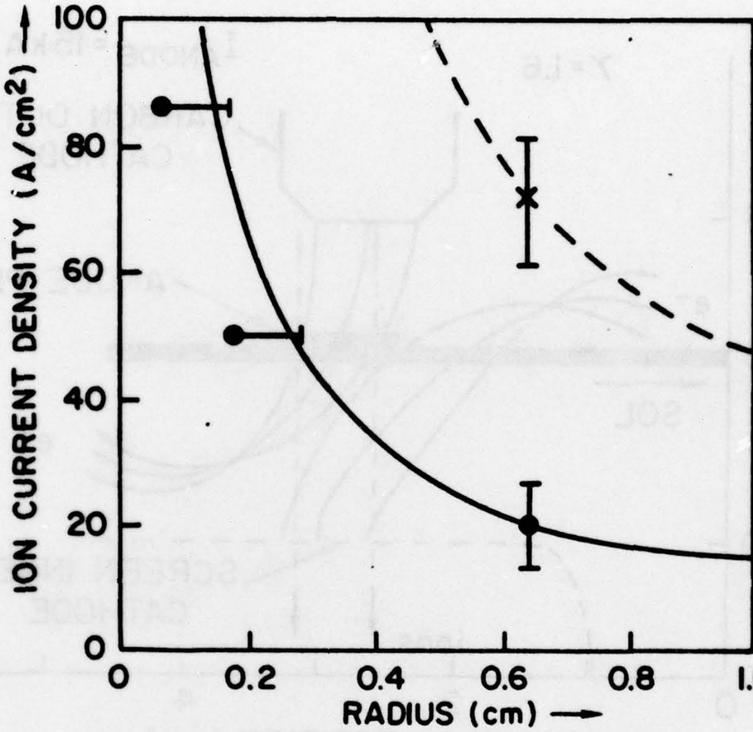

Fig. 4 — Inward ion current variation with radius